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An Ocean Surveillance Experiment Using HF

[Unclassified Title]

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November 1967

NAVAL RESEARCH LABORATORY
Washington, D.C.

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ABSTRACT
(Secret)

This report explores the use of HF backscatter radar in conjunction with an artificial ionosphere obtained by forming an electron cloud at E layer altitudes. An ocean surveillance experiment is suggested aimed at obtaining over-the-horizon HF radar coverage of ships a few hundred miles from the radar site.

PROBLEM STATUS

This is an interim report on the problem. Work on other phases of the problem is continuing.

AUTHORIZATION

Project RF 001-02-41-4007
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AN OCEAN SURVEILLANCE EXPERIMENT USING HF
(Unclassified Title)

INTRODUCTION

There is current interest in using surface wave propagation with a ship mounted HF radar as a means for detecting low altitude airborne targets; such a system might provide over the horizon coverage out to 100 nmi. A surface wave radar with such a capability will also be an effective skywave radar part of the time, that is, during the middle daylight portion of many days the radar will be able to detect aircraft out in the 500 to 700 nmi region using the ionosphere for refraction. The existence of this potential suggests that means for artificially creating a refracting ionosphere is worth investigation.

Also, recent developments in hf radars and their over-the-horizon capabilities has led to consideration of their use in detecting, tracking and possibly identifying stationary and slow moving targets such as ships at sea, cities, mountains, sea state and other geographical features. The desirability of such a capability is obvious. Ship traffic surveillance over large areas of the ocean could be accomplished. Stationary geographical features could be used as radar calibration signals for both range and amplitude in the study of natural phenomena as well as for detection of man-made targets.

The possibility of attaining this capability by relatively minor modifications to existing radars and in radar systems currently in the planning or construction phases is extremely attractive.

Normally over-the-horizon radars attain long range capability by using the ionosphere as the propagation medium. The ionospheric refractive properties are used to bend HF radio waves back toward earth for purposes of communication, target detection, etc.

This report will explore using HF backscatter radar signals with a simulated ionosphere. The simulated ionosphere will consist of an electron cloud released at E-layer altitudes for the purpose of reflecting radio waves back to the earth. The obvious advantage of obtaining long range radar capability independent of the ionospheric conditions is one of the objectives of the proposed technique. Also range of frequencies available for over-the-horizon use can be extended by a factor of two or more. Improvement in over-the-horizon radar capability and communication in the auroral zone is also a strong possibility. Other more specific operational advantages will be discussed in detail later.

RADAR CHARACTERISTICS

In principle, given the proper characteristics the type of radar system used can be coherent pulse doppler, continuous wave doppler or the frequency modulated Chirp-type radar.

There are in existence a number of HF coherent pulse doppler radars of proven high performance and which are properly located and can be made available for experimentation. For this reason, the rest of this report will only consider this type of radar. However, the analysis can quite easily be translated into terms applicable to both C.W. and F.M. radar.

The coherent pulse doppler radar can make measurements of signal amplitude, slant range and doppler frequency. Assuming that an unambiguous slant range is desired then the maximum unambiguous doppler frequency becomes half the pulse repetition rate required for that range. This should not prove to be a serious limitation for a target whose maximum speed is that of a surface ship.

In general two kinds of discrimination are used for detection, namely, amplitude discrimination and doppler frequency discrimination.

Amplitude Discrimination

Recent reports have indicated that stationary and near stationary targets can be detected and identified by amplitude discrimination alone. A study made by J.G. Steele[1] showed that over-the-horizon backscatter reflections from land areas are 10 decibels down in amplitude from similar reflections from sea areas, the sea state not being specified. A report by the Electro Physics Laboratory of I.T.T. indicates that mountainous regions and cities can be detected by amplitude discrimination and can be distinguished from surrounding environments of either land or sea.[2] For example, detection of islands in the Caribbean Sea have been attributed to reflections from the mountains on the islands. Detection probability for both the cities and mountains was of the order of 20%. Cross sections are of the order of 1 X $10^5 m^2$. Dr. L. Wetzel of the Institute for Defense Analyses recently explored the possibility of distinguishing forests from surrounding flat terrain by virtue of the vertical tree trunk geometry.[3] Other studies concerned with HF backscatter from trees[4], ground[5] and buildings[6] have been made.

In principle, if the ground area being illuminated by the radar can be resolved into small enough cells, then targets with large differences in reflection coefficient can be distinguished from one another. The minimum size of the radar cell depends on the radar azimuthal beamwidth and the pulse width. The cross section observed in the absence of noise depends on the size of the cell being examined and the power reflection coefficient or

$$\sigma = (P.W.) (R) (\theta) (\sigma o)$$

where σ = radar cross section of the backscatter clutter in the radar cell.

P.W. = pulse width in radar distance

R = average slant range to illuminated area

θ = beamwidth in radians

σo = reflection coefficient.

Measured values of σo have been made by I.T.S.A. and Naval Research Laboratory and fall between 1×10^{-2} and 1×10^{-3}. Assume $\sigma o = 5 \times 10^{-3}$ for purposes of calculation.

There are three HF radars located in the United States which are currently examining the problem of over-the-horizon detection of stationary and near-stationary targets. These are the Madre radar at Naval Research Laboratory, Washington, D.C., the Chapel Bell radar at the Electro Physics Laboratory of I.T.T. near Washington, D.C. and an I.T.S.A. radar located near Boulder, Colorado.

The Madre radar has not been able to discriminate via amplitude alone geographical features, sea state, etc. It uses beamwidths of 10° to 30° and a pulse width of 300 µsec. Assuming an average slant range of 1200 km for over-the-horizon distance to the radar cell, the illuminated area becomes approximately $10^{10} m^2$ for 10° beamwidth and $3 \times 10^{10} m^2$ for 30° beamwidth. The minimum cross section for the 10° beamwidth is

$\sigma(10^\circ) = \sigma o$ (Illuminated area) $= 5 \times 10^{-3} \times 10^{10} = 5 \times 10^7 m^2$. This becomes larger than $10^8 m^2$ for 30° beamwidth.

Targets of sizes near $1 \times 10^5 m^2$ would contribute about 0.1% to the total amplitude. If we further consider that in the normal backscattered signal fades of the order of 20 dB are common, then we must conclude amplitude discrimination is not possible with this radar. With larger slant ranges everything becomes worse.

The Madre radar is capable of using pulse widths of 15 microseconds. In this case a $1 \times 10^5 m^2$ target would contribute a maximum of about 10% to the total amplitude. When the magnitudes of the fades are considered, it is doubtful if the probability of detection could be raised to a suitable value without extensive changes.

For the I.T.T. Chapel Bell radar, $\theta = 3^\circ$, pulse widths vary from 10 to 50 microseconds. A computation similar to that made for the Madre radar yields.

$\sigma =$ (10 microsecond pulse) $\doteq 5 \times 10^5 m^2$

A target whose size is $10^5 m^2$ would add a substantial amount to the amplitude in this radar cell, but the detectability would be degraded by the normal fading rate. From a statistical point of view detection should probable. It all reduces to the probability of detecting 6 decibel changes in amplitude in the presence of slow 20 decibel fades. For the 50 microseconds pulse width, detection would be marginal, at best.

For the I.T.S.A. radar, $\theta \doteq 2^{\circ}$ and the pulse width is fixed at 300 microseconds. Computation yields

$$\sigma \doteq 1 \times 10^7 m^2$$

and detection of a $10^5 m^2$ target would be improbable. I.T.S.A. has not reported discrimination of geographical features, sea state, etc., from amplitude discrimination alone.

In summary, the three radars cited are not capable of a high probability of detection by amplitude discrimination alone. Improvements can be made by narrowing the pulse width or beamwidth.

Pulse widths can be narrowed below 10 microseconds, but other problems arise. As the pulse grows narrower, the required bandwidth becomes larger and eventually the ambient noise interference will limit the improvements that can be attained. In addition degradation of the pulse width by the ionosphere will be a limitation when such degradation becomes an appreciable part of the pulse width.

Beamwidth narrowing is probably limited to about 1° absolute value, so that appreciable improvement will only occur for the NRL case and tend to make detection marginal.

It appears that improvements could be made which would result in total gain of about one order of magnitude but with substantial effort and cost.

Doppler Frequency Discrimination

Even if amplitude discrimination were to yield satisfactorily high probabilities of detection after further improvements, it would seem desirable to investigate techniques in which the backscatter signal from a small target would not have to compete with the ground backscatter clutter which is normally present in over-the-horizon radars. One well known technique is spectrum analysis of the backscatter signals. The technique has been used successfully by various groups to distinguish between fast and slow moving targets. The Naval Research Laboratory Madre radar monitors aircraft traffic and missiles regularly via over-the-horizon radar in the presence of backscatter clutter whose amplitude is often several orders of magnitude larger than the detected target at the same range.[7] In addition to providing a signal which doesn't compete with the clutter, doppler frequency measurements yields accurate relative velocity information.

The dynamic range required to detect small signals in the presence of large signals has already been attained, so all that is required is that the motion of the desired target be distinguishable from the motions which are normally observed by over-the-horizon backscatter radars. These are due primarily to ionospheric motions, perhaps complemented by motions of natural objects on the ground or sea; for example, sea waves. Airplane velocities and missile velocities are clearly much higher than these naturally induced motions except near broadside aspect angle. It has not been clear that ship doppler frequencies are outside the band of doppler frequencies arising from natural phenomena.

It has been known for a number of years that the ground (or sea) backscatter in HF radar is characterized by amplitude fading, generally attributed to ionospheric motions, which can be analyzed as a band of doppler frequencies. Until recently it had been believed that this band of frequencies extended from zero doppler frequency to about 4 or 5 hertz where it was some 60 decibels down from the peak which presumably occurred at zero doppler frequency. On the basis of this belief, rejection notch filters with an inverse characteristic, i.e., maximum rejection at zero doppler frequency, have been built and used successfully to reject the large amplitude backscatter echoes from zero to five hertz. Notches have had more than 80 decibels of rejection at the carrier frequency (zero doppler frequency).[8]

Recent doppler frequency analyses of ground backscatter have indicated that the spectrum lies in an interval of $\pm$ 3 hertz from the carrier but doesn't necessarily peak at zero doppler frequency. It shows the signal peaking at a point somewhere in the interval of $\pm$ 3 hertz from the carrier, but only about 0.5 hertz wide some 30 decibels down on the skirts. There are indications that for appreciable times the spectrum stays quite narrow down to 60 decibels.[9] The exact spectral position of the peak can vary considerably in the frequency interval over a few hours, and occasionally the spectral width (at 30 db down) attains a width of one hertz, but normally the position peak is fairly stable over intervals of several minutes.

Frequently the spectrum analysis shows two peaks, often symmetric in both frequency and amplitude around the carrier. The double peak phenomenon has been attributed to ocean wave motion by some observers. Others have attributed it to wave motion in the ionosphere. In either case, a slow target moving, for example, at 30 knots would show up as a 3 hertz signal at 30 MHZ carrier frequency. The signal would be offset from the ground backscatter signal and would not directly compete with it, but would only compete with the noise in the band. The bandwidth then can be narrowed to a value consistent with the best balance between improved signal to noise ratio and range resolution.

Recently both NRL and ITSA have shown doppler frequency analyses of backscatter.[10] From the ITSA study, it was obvious that much more work will have to be done before any positive statements can be made regarding the identification of land versus sea areas by doppler analysis.

Based on the NRL and ITSA spectrum analyzed data, Dr. L. Wetzel made a study in which he showed the desirability of further exploring the concept of doppler discrimination as applied to ship detection.[11]

EXPERIMENTAL TECHNIQUE

For examining ships at sea for surveillance purposes, it would be desirable to define the ship characteristics uniquely so that a target could be recognized as a ship on the radar display.

For this purpose it is proposed that an artificial electron cloud be used as a reflecting surface to examine a moving ship via over-the-horizon radar. If such a scheme is attempted and is even partially successful, there are enough bonuses to be gained from the side issues to make it worthwhile even if it establishes that ship surveillance is unfeasible. The bonuses will be apparent in the discussion.

The artificial electron cloud will be used in place of the natural ionosphere. It will be a highly reflecting cloud in the HF band with an instantaneous fading rate appreciably lower than that of the normal ionosphere. It should be stable for several minutes if properly placed even under adverse circumstances. It can be used at night when noise levels are appreciably lower near the high end of the HF band and can be used at frequencies at least up to 50 MHZ and possibly as high as 100 MHZ if even lower noise levels are desired. If it is used during the daytime, solar flux will photoionize some of the release products and add several minutes to the cloud life, up to thirty minutes. It will effectively act as a large flat plate reflector for several minutes.[12, 13, 14, 15, 16]

In the ideal case, where there is no cloud motion (no fading rate), any fluctuations will be due to ground targets and the target characteristics can be determined. For example, a target ship can be made to maneuver and its cross section and doppler frequency spectrum can be measured as a function of the polarization angle or aspect angle, etc., of the incident wave. It is likely that the ground or sea clutter will be of larger amplitude than that of a ship. Doppler analysis can be used to distinguish between the clutter and the ship whenever the ship velocity relative to the incident wave is high enough to place the doppler frequency outside that of the clutter which in practice will have a finite bandwidth.

In the event it is discovered that the reliability of ship detection is not improved because of competing motion in the backscatter signal, useful information can be uncovered about the area of illumination. For example, the clutter amplitude measurements and doppler frequency measurements

should make clear if land and sea clutter can be distinguished from one another via doppler frequency analysis or from amplitude analysis, since the motionless reflector will not produce the deep fades characteristic of the normal ionospheric propagation. It should therefore be easier to distinguish amplitude differences of 6 db since those will no longer be complicated by simultaneous 20 db fluctuations. Reflections therefore from mountains on islands should be distinguishable both by reason of amplitude and zero doppler if the radar cell is small enough. By the same token sea wave motion should be measurable via doppler frequency analysis, so that some characteristics of the sea state should be measurable.

The above analysis is an idealization of the true conditions. All evidence indicates that motions do exist in released electron clouds and that at times fading rates via doppler frequency analysis can approach those observed in natural ionospheric propagation. However, most of the time the fading rate is less than that of the natural ionosphere, i.e., of the order of tenths of a hertz with a very narrow spectrum. If this fading rate becomes a problem in the proposed experiment, it can be dealt with at least partially by comparing the direct reflection from the electron cloud to the receiver to the reflection received from the ground beyond the cloud to the receiver. The ground backscatter should have some motions directly associated with the cloud motions and by judicious use of delays, the two received signals can be compared directly and similar motions cancelled by already established techniques. The net signal return then would have a larger percentage of ground target information in it than similar backscatter studies via the natural ionosphere.

An electron cloud payload launched from Wallops Island and released at 100 km altitude would provide near optimum conditions for exploration of the technique by both the Chapel Bell radar and the Madre radar. The ITSA radar would have the opportunity of observation in the one hop over-the-horizon mode.

Operational use would depend on the useful cloud duration and the coverage, i.e., the area of possible surveillance. This will be discussed in detail in the next section.

ELECTRON CLOUD TECHNOLOGY

Electron cloud releases at altitudes near 100 km is a well developed and well explored technology.[12-17] Extensive work has been done under Project Firefly. The payload release is accomplished with a high explosive which heats up the cesium in the payload producing centerpoint electron densities of the order of 10^9 electron/cc for a payload of 18 kg. The clouds have been probed with frequencies from 3 MHZ up to 150 MHZ regularly. The duration of radar echoes vary from two hours at the lower frequencies to a few seconds at 150 MHZ. Much work has been done at three frequencies, 30 MHZ, 50 MHZ, and 150 MHZ. For nighttime releases, cloud durations from

6-10 minutes are regularly observed at 30 and 50 MHZ.[19-22] During the daytime, electron densities are enhanced by photoionization of the cesium by solar flux, and regular durations observed are of the order of 30 minutes or more at 30 MHZ and 50 MHZ. The returns at 150 MHZ are of a few seconds duration both day and night.

The extent of a possible surveillance area is not known precisely but results from Project Red Lamp[18] and Project Firefly can give an estimate. In Project Red Lamp the electron cloud release was made at 120 km at 2:00 A.M. L.S.T. and was examined in detail during the period of initial expansion (approximated 0.5 sec) by both monostatic (backscatter) and bistatic (forward scatter) C.W. radars in the HF band. One third of a second after release, all observers (forward and backscatter) reported cross sections of about 1 X $10^6 m^2$, indicating an initial spherical expansion. The locations of the observing sites indicated that the minimum radius of ground coverage was about 200 nmi (370 km) in all directions for a total effective surveillance area of 120,000 nmi^2 or 430,000 km^2. These values do not imply that the effective area seen by monostatic backscatter radar would be as large. They only indicate that widely dispersed radar receiving stations obtained signals of sufficient strength for a crude cross section calculation. The geometrical configuration of the receiving sites involved both backscatter and side scatter. After initial expansion the cloud was observed to expand slowly and reached its largest value a few minutes after release but the details were not investigated. Although the release was made near the least optimum time of day (2:00 AM LST) and not at the optimum altitude, substantial returns directly from the cloud were observed on both backscatter and side scatter modes for a period of minutes after release.

Scatter from a spherical cloud leads to ambiguities in range. If the cloud is deposited in the 100 km region (the optimum region as determined experimentally) where the wind shears are strong then after initial expansion the longer lasting parts of the cloud will more and more resemble a flat plate so that the scattering in the forward direction will be favored over that in other directions. Experiment bears this out.[13,14] The relatively "flat" plate comes from the fact that below 90 km altitude or so recombination quickly depletes the electron cloud and above 110 km altitude pressure equilibrium leads to low densities and the cloud dissipates more quickly. Experiment also bears this out.[13] Optimum electron cloud altitude has been found to be approximately 100 km $\pm$ 5 km.

Forward scatter HF communications experiments under Project Firefly can give an estimate of the effective surveillance area provided by an electron cloud after initial expansion has taken place.

In these experiments, one transmitter of 1 kw average power was used in conjunction with several receiving stations positioned at ranges up to 1800 nmi in front of the transmitter and at various angles from the azimuthal beam boresight direction. When the electron cloud was released at 100 km altitude at about 200 nmi in front of the transmitter, receivers in the

direct path received the best signals. Substantial signals have been received simultaneously at 400 nmi and 1400 nmi from the transmitter via the electron cloud. Occasional signals were received up to 1800 nmi range from the transmitter. Receivers located at equal ranges within $\pm 10^{\circ}$ from the boresight direction received substantially the same signal strength from nearly below the cloud out to 800 nmi range. Receiving stations which were more than 30° away from boresight received signals considerably lower in amplitude (approx. 20 db) than those within the 10° region.

These experiments give an estimate of the effective area of forward scatter, i.e., the area below and beyond the electron cloud. Using the 10° beamwidth and the distances indicated above, a crude estimate of the effective surveillance area would be 160,000 miles^2 or equivalent to a 400 mile square. The effective beamwidth supplied by the cloud will not vary appreciably with frequency.

Electron cloud duration is strongly dependent on release altitude. The release must take place between 95 km and 105 km altitude for maximum duration. Currently there are two methods of boosting the payload to this altitude and both methods have proven to be highly reliable.

The traditional method is to use a two stage rocket like the Nike-Apache or Nike-Cajun. The specific type of rocket used depends on the payload-altitude requirements as well as the availability of the rocket.

A newer method of attaining proper altitude is by the use of the Project Harp technique in which the payload is fired from a gun.[23] Suitable electron cloud payloads and many equivalent payloads have been successfully tested on a regular basis at the Barbados site which uses a 16 inch Navy gun for payload launches. The advantages of using the 16 inch gun are improved repeatability and low cost.

In the proposed experiment no operational 16 inch gun is close enough to the operational radar to be of any use.

On Wallops Island currently a 7 inch gun is being tested for placing 10 lb. payloads at 100 km altitude. This gun has a barrel length of about 60 ft. which is too long for shipboard use. There are in existence shipboard rocket launchers which could be used for the cesium payload. Wallops Island lies close to both the NRL radar and the I.T.T. radar. Wallops Island can also be used as a rocket launch site.

It is proposed that several 18 kg payloads be obtained and launched via rockets from Wallops Island at night. If the 7 inch gun goes into successful operation, then suitable payloads can be acquired and advantage taken of the low cost of use of the gun. It is suggested that airline schedules and ship schedules in the vicinity of Bermuda be acquired, since airplane detection can be used as a type of calibration

signal by the NRL radar. The payloads should be launched preferably at night to take advantage of the low noise conditions. Since the effective beamwidth of the cloud doesn't change with frequency, the highest possible frequency in the HF band should be used to further take advantage of the noise conditions. This can be done also during the daytime, if one chooses to take advantage of the longer cloud life that the daytime provides. At the higher frequencies the daytime D layer losses would cause no problems. A launch azimuth toward Bermuda is suggested since air traffic can be used as a calibration, and ship traffic can be used as targets and there is a possibility of detecting the islands themselves.

Payloads can be provided by Space Data Corporation of Phoenix, Arizona. The total cost of acquiring and firing a payload via rocket launch is approximately $10,000 per payload. Probability of total success is about 80%. Mr. Edward Allen of Space Data claims that the payloads can be stored indefinitely.

For the gun launched payloads, the total cost is approximately $2500 with a probability of success near 90% for the 16 inch Barbados gun and a yet to be determined figure for the 7 inch gun at Wallops Island.

When the 7 inch gun can be used successfully, then the 10 lb - 20 lb payloads should be suitable for further tests, especially in the daytime when the electron density becomes enhanced.

On the other hand if a smaller effective beamwidth is desired for study purposes, then perhaps the smaller payloads would be suitable.

SUMMARY OF OBJECTIVES

In summary, a major objective of this experiment would be to determine the radar characteristics of a ship in an OTH mode taking into account aspect angle and polarization without the added complexities of ionospheric motion. This would have the two-fold result of measuring the feasibility of such detection as well as providing a recognizable signature if successful.

Another major objective would be to extract features unique to the specific backscatter clutter to determine whether or not it is from land or sea and whether or not specific large geographical features can be recognized, i.e., mountain ranges or large bodies of water; cities, etc., by both amplitude and doppler analysis.

A third objective of such an experiment would be the evaluation of the technique in terms of an operational ocean surveillance system. Because its usefulness extends far above the HF region (more than 50 MHZ) and because it can be used at night as well as daytime, the lower noise levels at the higher frequencies make it attractive.

SOME OPERATIONAL CONSIDERATIONS

For ships at sea which can carry suitably sized guns, payloads can be acquired and launched from the ships at sea for purposes of communication or for surveillance. A modest sized radar located on the ship designed for operation near or above 50 MHZ could be used for over-the-horizon surveillance or communication up to several hundred miles from the ship. In such a case the skip distance would no longer represent a limitation to coverage, since the cloud can be released nearly overhead to detect targets just beyond the horizon as well as at longer ranges.

Alternately a shore based radar could use the ship launched cloud independently of or simultaneously with the ship's radar for surveillance or communications at longer ranges.

Such an electron cloud could also be used with a vertical polarized ground wave radar to provide continuous coverage from zero range out to several hundreds of miles.

Finally, if initial studies are moderately successful, consideration should be given to similar releases in the auroral zone, for example, from Ft. Churchill, for determining if radar capability and communications can be improved. Direct examination of the cloud with a pulse backscatter radar, even at long range should be able to detect cloud behavior which would indicate the further steps to be taken.

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11 SUPPLEMENTARY NOTES	12 SPONSORING MILITARY ACTIVITY Dept. of the Navy (Office of Naval Research) Washington, D.C. 20360

13 ABSTRACT

(SECRET)

This report explores the use of HF backscatter radar in conjunction with an artifical ionosphere obtained by forming an electron cloud at E layer altitudes. An ocean surveillance experiment is suggested aimed at obtaining over-the-horizon HF radar coverage of ships a few hundred miles from the radar site

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14 KEY WORDS	LINK A		LINK B		LINK C	
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Aircraft detection						
HF radio waves						

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MEMORANDUM

20 February 1997

Subj: Document Declassification

Ref: (1) Code 5309 Memorandum of 29 Jan. 1997
(2) Distribution Statements for Technical Publications NRL/PU/5230-95-293

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Memo: 1251, 1287, 1316, 1422, [redacted], 1500, 1527, 1537, 1540, 1567, 1637, 1647, 1727, 1758, 1787, 1789, 1790, 1811, 1817, 1823, 1885, 1939, 1981, 2135, 2624, 2701, 2645, 2721, 2722, 2723, 2766. Add 2265, 2715.

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